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ACOUSTOELASTIC EFFECTS IN AUTOFRETTAGED STEEL CYLINDERS

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Residual stresses in short cylinder sections cut from autofrettaged larger steel tubes have been measured by means of the acoustoelastic effect. Ultrasonic shear waves polarized along the hoop and radial direction and propagating in the axial direction, as well as longitudinal waves, were used. Calibration specimens cut from similar type material were used to determine the velocity changes of longitudinal and shear waves propagating perpendicular to an applied
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stress. Third order elastic constants were derived from these measurements. Velocity measurements for zero applied stress along different axes of the cube-shaped calibration specimens indicate the presence of orthorhombic texture. Stress distributions and texture dependent effects within the cylinders have been determined.

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INTRODUCTION

Ultrasonic velocity measurements are commonly used to determine stresses in materials. Determination of the stresses from the sound velocities generally requires knowledge of the second order or Lame' constants and third order elastic constants (refs 1-3) introduced by Murnaghan (ref 4) in his treatment of finite deformations.

Stresses are often introduced into materials by processes such as autofrettage or thermal quenching. The materials in question, however, may also have been subject to other treatments such as cold rolling or forging. These latter processes are known to introduce so-called "texture effects," i.e., anisotropic orientations in polycrystalline materials. Texture effects can have a profound influence on ultrasonic velocities. Conversely, information on the crystalline orientation distribution function can be derived from ultrasonic velocity measurements (refs 5,6).

This report deals with elastic and texture properties of autofrettaged cylinders made from ASTM A723 steel. Autofrettage is a process in which a hollow cylinder is deformed into the plastic region by application of internal pressure. Releasing the pressure establishes compressive and tensile hoop stresses near the inner and outer diameter of the cylinder, respectively. Compressive radial stresses also result inside the cylinder. In addition, texture can be present within the cylinder due to rotary forging before the application of autofrettage.

References are listed at the end of this report.

The specimens used in this work were short circular cylinder sections cut from long autofrettaged tubes which had undergone different amounts of plastic deformation. Ultrasonic velocity measurements were made for shear waves polarized along the hoop and the radial direction and propagating in the axial direction. Longitudinal waves propagating along the axial direction were also used.

For calibration purposes, two auxiliary types of experiments were performed on rectangular prisms cut from the cylinders. First, stress-velocity relations were determined from ultrasonic velocity measurements for transverse and longitudinal waves propagating perpendicular to an externally applied stress. The third order elastic constants ℓ, m, and n were also determined from these experiments. Second, texture effects were investigated by performing velocity measurements for the nine combinations of the propagation direction (axial, hoop, and radial) and the type of ultrasonic wave (longitudinal and the two polarization directions of the transverse wave).

THEORETICAL CONSIDERATIONS AND RESULTS OF CALIBRATION MEASUREMENTS

Theoretical Stress Distributions

Assuming the conditions of plane strain, incompressibility, and ideal plastic behavior together with the von Mises' yield criterion, the residual hoop, radial, and axial stresses σ_θ, σ_r, and σ_z in a circular cylinder can be written in closed form as functions of the radial coordinate (ref 7). The solutions fulfill the boundary conditions

$$\sigma_r(a) = \sigma_r(b) = 0 \tag{1}$$

and

$$\int_a^b \sigma_\theta dr = 0 \quad , \tag{2}$$

where a and b are the inner and outer radius, respectively, and the equilibrium condition

$$\sigma_\theta = \sigma_r + r \frac{d\sigma_r}{dr} \quad . \tag{3}$$

Predicted hoop stresses are compressive and tensile at the inner and outer diameter, respectively. Predicted radial stresses are always compressive and typically one order of magnitude smaller than the largest hoop stresses. Axial stress is given by one-half the sum of hoop and radial stress. However, cutting short cylinder sections from longer tubes, as done in the present experiment, is expected to relieve the stresses along the axial direction.

Stress-Velocity Relations

Relations between ultrasonic velocities and residual stresses can be obtained from the theory of finite deformations. The analysis superimposes an infinitesimal deformation, represented by the ultrasonic wave, on a finite static deformation due to the residual stress. The stress-velocity relations are expressed in terms of the Lame´ or second order elastic constants λ and μ, and the third order or Murnaghan constants ℓ, m, and n. The expressions for the stress-strain tensor from which the stress-velocity relations for the general case of triaxial stress can be derived have been given by Hughes and Kelly (ref 1). Explicit expressions for the velocity relations in the case of uniaxial stress can also be found in their study.

The velocity change Δv_{12} of a shear wave, propagating in an isotropic medium along the 1-axis and polarized in a direction perpendicular to it (arbitrarily chosen as the 2-axis) is given in terms of the aforementioned elastic constants and the finite stresses σ_i along the three principal axes as follows (ref 3):

$$\frac{\Delta v_{12}}{v_{os}} = \frac{1}{6\mu K_o}\left[(3\lambda+2\mu)\sigma_1 + (3\lambda+2\mu+\frac{3n\lambda}{4\mu}+\frac{n}{2})(\sigma_1+\sigma_2)\right.$$
$$\left. + (m-\frac{n}{2}-2\lambda-\frac{n\lambda}{2\mu})(\sigma_1+\sigma_2+\sigma_3)\right] , \qquad (4)$$

where $K_o = \lambda + 2\mu/3$ and v_{os} is the velocity in the absence of finite stresses. For the longitudinal wave propagating along the 1-axis one finds similarly, setting $v_{o\ell}$ equal to the longitudinal wave velocity in the absence of stress

$$\frac{\Delta v_{11}}{v_{o\ell}} = \frac{1}{4\mu(\lambda+2\mu)}(4\lambda+4m+10\mu)\sigma_1$$
$$+ \frac{1}{6K_o(\lambda+2\mu)}(2\ell-4\lambda-\frac{2m\lambda}{\mu}-\frac{2\lambda^2}{\mu})(\sigma_1+\sigma_2+\sigma_3) \quad . \qquad (5)$$

The coefficients multiplying the stresses in Eqs. (4) and (5) were determined from measurements of velocity changes of ultrasonic waves propagating through rectangular test bars with cross-sectional area 1/2 by 1/2-inch, perpendicular to the direction of applied tensile stress ($\sigma_1 = 0$). The test bars were cut from autofrettaged cylinders with the long dimension (the direction of applied stress) along the hoop direction. Partial results of these measurements have been reported previously (ref 3). For shear waves we obtained for the case where the polarization is parallel to the stress

$$(\Delta v_{12}/v_{os}) = (-7.80 \pm 0.30) \times 10^{-2}\ \sigma_2\ [10^5\ \text{bar}] \qquad (6)$$

and for polarization perpendicular to the stress

$$(\Delta v_{12}/v_{os}) = (0.57 \pm 0.10) \times 10^{-2}\ \sigma_3\ [10^5\ \text{bar}] \quad . \tag{7}$$

For longitudinal waves we measured

$$(\Delta v_{11}/v_{o\ell}) = (0.76 \pm 0.10) \times 10^{-2}\ \sigma_{2,3}\ [10^5\ \text{bar}] \quad . \tag{8}$$

Using the results of Eqs. (6) through (8) and the values of the Lame' constants λ and μ, which will be discussed in the next section, Eqs. (4) and (5) can be solved for the Murnaghan constants. Values obtained are $\ell = -38.8 \pm 3.6$, $m = -62.4 \pm 2.4$, and $n = -74.7 \pm 1.6$, in units of 10^5 bar.

The values of the elastic constants determined above in conjunction with Eqs. (4) and (5), can be used to predict velocity changes due to stresses along the direction of propagation. One obtains for shear waves

$$(\Delta v_{12}/v_{os}) = (-1.54 \pm 0.30) \times 10^{-2}\ \sigma_1\ [10^5\ \text{bar}] \tag{9}$$

and for longitudinal waves

$$(\Delta v_{11}/v_{o\ell}) = (-14.5 \pm 1.1) \times 10^{-2}\ \sigma_1\ [10^5\ \text{bar}] \quad . \tag{10}$$

It is worth noting that longitudinal waves are about ten times more sensitive to residual stresses along the direction of propagation than shear waves. The acoustoelastic constants in Eqs. (6) through (10) and the values of the Murnaghan constants given above are in reasonable agreement with values reported by other investigators for somewhat different types of steel (refs 8,9).

Sound Velocities in Cubic-Structure Materials With Texture

Rolling or forging of polycrystalline materials can introduce partial alignment of the individual single crystals, so-called texture, which causes a dependence of the ultrasonic velocities on the propagation and polarization direction. In the most general case, the material develops orthorhombic

texture, corresponding to three orthogonal planes of symmetry. A less complicated case is fiber texture which corresponds to a medium which is elastically insensitive to rotation about one axis. From symmetry considerations, one would argue that this axis should coincide with the direction of the striking force during forging.

The ultrasonic velocities v_{ij}, where i refers to the propagation and j to the polarization direction, are given as (refs 5,6):

$$\rho_o v_{ii}^2 = \lambda + 2\mu + 2ct_{ii} \tag{11}$$

and

$$\rho_o v_{ij}^2 = \mu + ct_{ij} \quad , \tag{12}$$

where $c = c_{11} - c_{12} - 2c_{44}$ in terms of the elastic constants of the cubic single crystal. Expressions for the texture factors t_{ij} are also given in References 5 and 6. It is worth noting that $t_{ij} = t_{ji}$ and that

$$\sum_j \rho_o v_{ij}^2 = \lambda + 4\mu \tag{13}$$

which is independent of texture.

Measurements were performed on a rectangular prism with dimensions 1/2 by 1/2 by 5/8-inch cut from an autofrettaged tube with its surfaces parallel to the axial, hoop, and radial direction which will be labeled 1, 2, and 3, respectively. Velocity measurements were performed with the pulse-echo overlap technique. Ten and fifteen MHz longitudinal and five and fifteen MHz shear transducers were used in order to arrive at an unambiguous identification of the correct pulse overlap (ref 10). Table 1 lists the corresponding elastic constants $\rho_o v^2$ ($\rho_o = 7.84 \times 10^3$ kg/m^3) along with the sums of Eq. (13). The results indicate that Eq. (13) is fulfilled to a high degree of accuracy.

TABLE 1. ELASTIC CONSTANTS $\rho_o v_{ij}^2$ IN UNITS OF 10^5 BAR

	i=1	i=2	i=3	$\sum_i$
j = 1	27.0170	7.9591	8.0176	42.9937
j = 2	7.9541	27.0289	7.9971	42.9801
j = 3	8.0151	7.9921	26.9728	42.9800
$\sum_j$	42.9862	42.9801	42.9875	

The data in Table 1 indicate the presence of texture; furthermore, to first order, it appears to be fiber texture. In the case of fiber texture where there is one elastic axis, the two longitudinal waves propagating perpendicular to it are equal in velocity. Of the transverse waves, the two polarized and propagating perpendicular to the elastic axis are equal and differ from the remaining four which are in turn equal to each other. The fact that this last condition is violated to some degree indicates that the texture is more precisely characterized as orthorhombic.

By forming averages of the values in Table 1, we derive $\lambda = 11.03 \times 10^5$ bar and $\mu = 7.99 \times 10^5$ bar for the Lame´ constants in this particular specimen.

RESULTS FOR AUTOFRETTAGED CYLINDERS

Experimental Details

The specimens for these experiments were right circular cylinders, one to two inches in height, with inner radius a and outer radius b of approximately three and six inches, respectively, which had been cut from longer

autofrettaged tubes. Velocity changes were determined by measuring the change in return time of one echo (typically the fifth) with respect to a reference time which was chosen as the return time near the outer diameter for the shear wave polarized in the hoop direction (ref 3). Return times for the radially polarized wave were determined by rotating the transducer. A separate reference, also near the outer diameter, was used for longitudinal waves. Standard commercial transducers were used in these experiments. The time resolution of the experiment was better than 5 ns, thus relative velocity changes were determined to better than one part in 10^4.

Determination of Texture and Stress From Experimental Velocity Distributions

Figures 1 and 2 show the observed velocity changes for the longitudinal (full diamonds) and the two transverse waves (full circles and squares for polarization in the hoop and radial direction, respectively) with radial distance, plotted vs. (r-a)/(b-a). Some qualitative features are immediately obvious. First, the shear wave polarized along the hoop direction exhibits large velocity changes with radial position. If we establish a base line for the velocity in the zero stress state using the boundary condition Eq. (2), and the proportionality between stress and relative velocity change, the measurements indicate compressive and tensile hoop stresses near the inner and outer diameter, respectively. Second, the shear wave polarized along the radial direction is displaced toward larger velocities from the base line established above. In view of the boundary conditions (Eq. (1)), this cannot be due to radial stresses. The direction and magnitude of the displacement is approximately the same as for the calibration specimen of Table 1 and

therefore can be explained by a texture effect. Third, velocity changes for the longitudinal wave are comparatively small. In addition, since the acoustoelastic coefficient in Eq. (10) is rather large, it follows that residual longitudinal stresses are small as expected and can be neglected in the analysis of the transverse wave velocities.

The major contribution to the observed texture effect appears to be independent of the radial position and thus does not influence the analysis for hoop stresses in which the zero-stress base line is established through application of the boundary condition Eq. (2). However, radius dependent texture effects are clearly present, most notably in Figure 1, which shows an oscillatory behavior in the velocity of the transverse wave polarized along the radial direction. This is at variance with expected radial stress distributions and the equilibrium condition Eq. (3) and must, therefore, be due to texture.

For the idealized situation of fiber texture with an elastic axis along the radial direction, theory predicts (refs 5,6) the texture factors in Eqs. (11) and (12) to be in a ratio of $t_{zr}:t_{z\theta}:2t_{zz} = -4:1:3$. That is, texture induced velocity changes will be most pronounced for the radially polarized shear wave and of lesser magnitude and opposite sign for the transverse wave polarized along the hoop direction and the longitudinal wave. This is indeed more or less the observed behavior for the oscillatory structure in Figure 1.

In view of the discussion above and since hoop stresses are expected to be typically one order of magnitude larger than radial stresses, $\Delta v_{z\theta}/v_{os}$ primarily reflects the stress distribution. The lefthand scales in Figures 1

and 2 for the hoop stress are drawn using the acoustoelastic constant of Eq. (6). Radial stresses, in addition to being small, enter through the small coefficient of Eq. (7) and can be neglected. The curves are drawn for 80 and 100 percent autofrettage, respectively, using a yield strength $\sigma_o = 0.12 \times 10^5$ bar (174 Ksi).

The open symbols in Figures 1 and 2 are obtained by subtracting from the measured velocity distributions the calculated contributions due to theoretical hoop and radial stresses. They reflect primarily the radial dependence of the texture factors which are expected to be of opposite sign for the radially polarized shear wave and the longitudinal wave. For fiber texture, the apparent variations in the relative velocity change are expected to be reduced by a factor $(3/4)(v_{os}/v_{o\ell})^2 = 0.22$ for the longitudinal wave as compared to the radially polarized shear wave. The variations in Figures 1 and 2 are reasonably consistent with this expectation. Thus, one might conclude that the velocity changes observed for the longitudinal wave also reflect texture and that residual stresses are indeed essentially zero as expected.

CONCLUSION

Velocity changes of shear and longitudinal waves propagating along the axis of short autofrettaged ASTM A723 steel cylinders can be used to derive information on residual stresses and texture effects. The shear wave polarized in the hoop direction shows little texture effect and can be used to yield information on the hoop stress distribution via the acoustoelastic effect. The shear wave polarized in the radial direction primarily reflects

variations of the texture factor with radial position, as does the longitudinal wave. Residual radial and longitudinal stresses are difficult to separate from texture effects, but longitudinal wave measurements are consistent with zero axial residual stress. Theoretical stress distributions can give a reasonable account of the measured hoop stresses.

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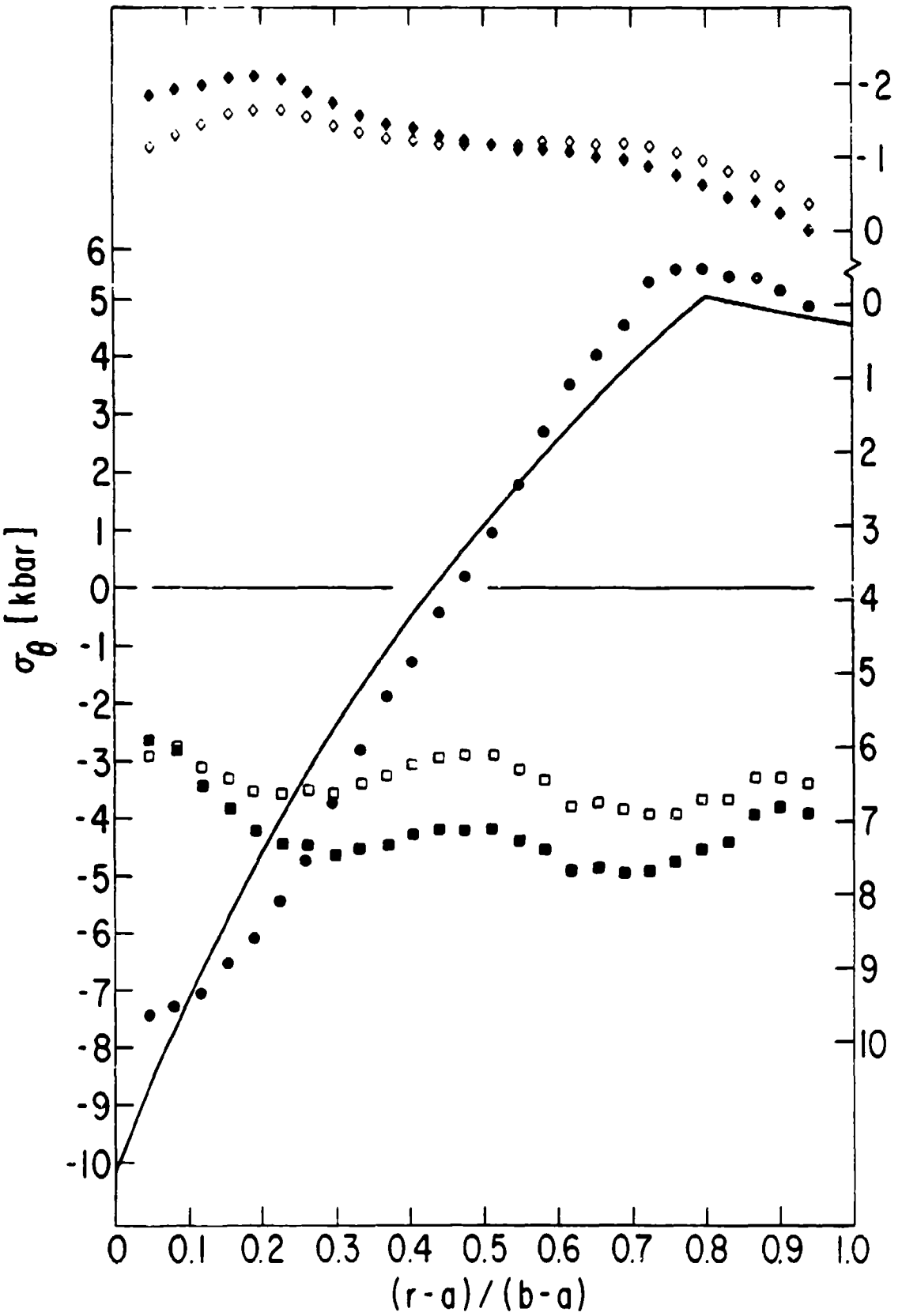

Figure 1. Relative velocity change for shear and longitudinal waves and hoop stress in an 80 percent autofrettaged cylinder.

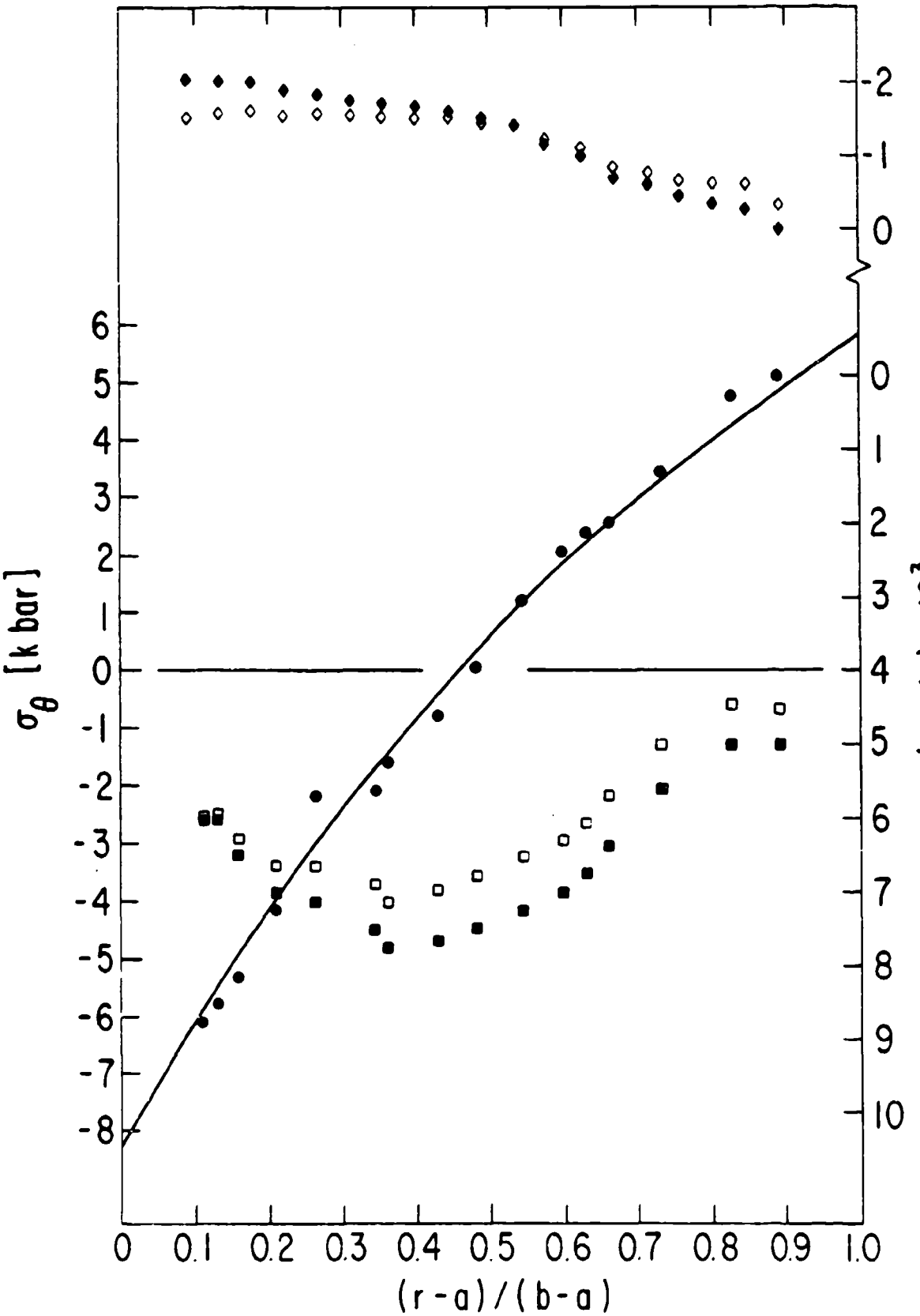

Figure 2. Relative velocity change for shear and longitudinal waves and hoop stress in a 100 percent autofrettaged cylinder.

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